

KEYNOTE ADDRESS In Search of the Perfect Weld

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Abstract

Over the past 100 years, welding and joining technology has progressed significantly such that it is now an essential part of virtually every manufacturing industry. Nonetheless, the pace of development of new processes has slowed considerably. Current research and development is primarily related to improvement of existing technologies. While such emphasis has important technological benefits, it does not provide the glamour and excitement of new developments which attract the attention of decision-makers. If the welding scientific community is to grow, it will be necessary to take greater risks rather than perform incremental research.

Introduction

At the International Institute of Welding Annual Assembly in Sydney, Australia in 1976, Richard Weck, then Director General of the British Welding Research Institute, made a presentation on the current state of the art in fusion welding [1]. While he noted the tremendous progress which had been made in the previous fifty years in welding technology, he lamented the absence of more recent progress in fusion welding. "Our ultimate objective must be to join metal as if it were made from one solid piece without flaw. To achieve this by fusion welding has proved elusive - and I fear illusory." *

In his concluding remarks, he suggested changes in direction toward technology such as high power electron beam or solid state joining technology such as friction welding or diffusion bonding. While he acknowledged that fusion welding (essentially arc welding) will be with us for many years to come, he lamented the complexity of the process and the inability to make significant strides in this technology.

As Dr. Weck did over two decades ago, it is often useful to take stock of where we are in order to help define our direction for the future.

* Weck 1976.

Historical

Welding is as old as metal-working itself. Ancient metalsmiths used forge welding or cast welding to join their wares. Soldering was also employed by the ancients. Nonetheless, the real growth of the metals industry began with the Bessemer process in the mid-1850's, when steel became the low-cost material of choice for construction of railroads, bridges, and buildings, and the world entered the Iron Age. Fortunately, the new technologies for joining metals also developed during the nineteenth century. In 1801, Sir Humphrey Davy discovered the electric arc and named it after the shape of an "arch," as his arc was struck in a horizontal position, and the buoyancy of the gases caused it to arch between the electrodes. The arc remained a scientific curiosity until the latter part of the nineteenth century when electrical power supplies became available. In 1885, Bernardos received a patent "for working metals in various ways by electricity, including a method of applying a fused metallic coating for ornamental or other purposes." His was a carbon arc, and he used a colored glass screen to protect the eyes of the workmen.

Indeed, throughout the history of welding technology, any new heat source, whether it be an electric arc or electric resistance, a laser, an electron beam, a particle beam, or simply intense light, is used to produce a fusion weld almost as soon as the technology develops an intense enough source of energy. Reportedly, Sir Humphrey Davy did weld with his arcs, and Elihu Thomson began resistance welding as soon as power sources of several thousand amperes became available. Lasers were used to repair the metal connections inside glass vacuum tubes without interrupting the vacuum as early as the late 1950's. Electron beam technology was used as soon as powerful sources became available in the 1950's and in the 1980's, particle beams, developed for military purposes, were used in an attempt to develop new welding technologies. The reason for this nearly immediate use of any new heat source for fusion welding technology is our relentless search for a better process.

We acknowledge that what we have is imperfect. Indeed, many people feel that welds are inferior to wrought metal. For example, one of my colleagues tells students that "something will not fail unless it has been welded." * Nonetheless, welding is ubiquitous. Virtually all manufactured products contain joints and the quality of these products is directly related to the quality of the joints which are produced. Welding and joining technology has improved what we manufacture. It has

- increased size
- reduced weight
- reduced cost
- improved reliability, and
- increased product life

There are, however, problems and limitations with current welding and joining technology. Joining is a relatively large fraction of the manufactured product cost, and it often comes at the end of the manufacturing cycle when the cost of scrap is high, because other processes such as casting and machining have already been performed.

Just as Professor Pelloux suggests, many failures have been caused by joining defects. There are, however, a number of reasons why this is so. The first is that even the best joints may have inferior strengths as compared to the base material. This is particularly true in materials such as heat-treated aluminum alloys, where the heat of fusion welding wipes out the beneficial effects of the heat treatment. While it may be possible to resolutionize and age the final structure in heavier, less complex parts; lighter gauge or complex parts would not be able to survive these additional thermal processes after welding. Hence, the joint efficiency of the weld in thermomechanically treated materials, as measured by simple tensile tests, is inferior to the base material properties. The second, and perhaps more important, reason why failures often occur at joints is that the joints are usually placed in the most highly stressed locations of the structure. Joints are naturally located at corners and edges which are geometric stress concentrations. Even if the weld is perfect, or even exceeds the strength properties of the base material, the failure will often occur at the weld because of geometric stress concentrations in the structure. Thus, failures often occur at welds, not because the welds are inferior but because of the location of the weld.

In addition to these problems, there are additional limitations on welding technology. Welding is often applied as an art. As noted above, virtually any new heat source is used to produce welds long before a scientific understanding of the process is developed. This is because of the immediate industrial need for any new joining process. In addition, welding is often applied manually, and hence is subject to the vagaries of the individual operators. Finally, welding is an extremely complex process with severe thermal gradients and dramatic changes in temperature occurring over relatively short periods of time. When the hot material interacts with the surrounding cold material, the thermoelastic behavior of the structure becomes too complex for even a simple model using the world's most

powerful supercomputers. For these reasons, much of what we do in welding is still applied as an art or by using empirical relationships or rules of thumb or standards and procedures which have proven effective in the past. This is not particularly reassuring when one is faced with a host of new materials demanding to have specialized welding procedures developed. Development of specific procedures for these many new materials is extremely time-consuming and costly, and limits our ability to economically use many of these very specialized materials in engineering structures.

Another limitation faced by nearly every nation is that very few engineers have been educated in welding and joining technology. In the United States, there is only one major four-year university with a degree program in welding. Most engineers who work on welding problems have never had a formal course in welding and are essentially self-taught. For a field in which so many scientists and engineers are "learning by doing," there is an astonishing lack of educational material across the entire range of technical levels. Most of what is available is of the handbook type and is not well-suited for engineers who are developing new materials and new technologies for joining them.

What is a Weld?

The American Welding Society defines a weld as "a localized coalescence of metals or non-metals, produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler metal" [2]. If one looks closely at this definition, one finds that it involves either a metal or a non-metal, the use of heat alone or pressure alone, or the two in combination, and the use of a filler metal or not. This is not a particularly useful definition. This tells how to make a weld, but it does not tell what a weld is. In fact, there are approximately one hundred different welding processes listed in the *AWS Welding Handbook*. Over the past one hundred years, virtually every combination of heat, pressure, filler material, and base material have been used to attempt new joining technologies. A definition which tries to describe how a weld is made is necessarily going to be cumbersome and confusing.

Perhaps a more useful approach is to define a weld in terms of the properties which are achieved. I prefer a definition of a weld as "the coalescence of two objects such that the properties of the joint are substantially similar to the properties of the base material or base materials being joined." This is not only a definition in terms of the properties of the joint, but it is also implicitly a definition in terms of the fitness for purpose, as the properties are defined by the requirements of the application. This necessitates an understanding of how the structure is to be used and hence, what properties and performance will be required of the joint.

There are a host of properties, some of which are outlined in Figure 1.

* R. M. Pelloux

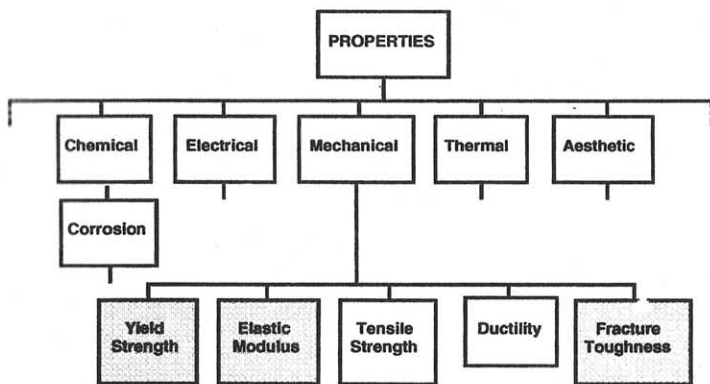


Figure 1

Partial Hierarchy of Material Properties

The properties may be chemical, electrical, mechanical, thermal, aesthetic, or others. These can be broken down further, such as mechanical properties, yield strength, elastic modulus, tensile strength, ductility, and fracture toughness. For most structures, the yield strength, fracture toughness, and perhaps elastic modulus are the most critical, as these define the strength of the structure. One of the problems is that few welds produce properties in the joint that are absolutely identical in all respects to the properties of the base material. For example, in terms of yield strength, there is a perennial question of whether one should have over-matching or under-matching yield strength in the weld metal as compared to the base material. The general consensus is that the weld joint should have a higher strength in most applications. This generally relates to the effective ductility or toughness, as an understrength weld metal will tend to concentrate the strains and hence reduce the observed ductility or toughness. Recent studies have shown that a 10% variation in yield strength between the weld metal and the base material can result in a 50% degradation of the fracture toughness as measured by conventional techniques [3].

For dissimilar materials, in which the modulus of the two materials is different, there will be an inherent stress concentration at the joint, not for geometric reasons but because of the variation in modulus across the joint. As can be seen from these brief examples, there is an increasing need to study the mechanics of inhomogeneous materials. One cannot assume that a weld joint is homogeneous or that the mechanical properties are not influenced by the local environment of the weld. Over the past fifty years we have spent a tremendous amount of time studying how microstructure influences properties of weld joints, but we have not spent enough time studying how the inhomogeneous mechanical properties across the joint influence the macroscopic properties of the joint.

From a practical point of view, "The perfect weld is the one that works." Nonetheless, as designers push the limits of materials and shave the safety factors which have been used for many years, fewer welds are "perfect" and the risk of failure increases. As more dissimilar materials are used in complex structures, it is becoming more difficult to find joints which can

match the properties of both base materials sufficiently well to be fit for the intended purpose.

The Pace of Progress

As Richard Weck noted in his IIW address in 1976, it is difficult to eliminate the problems of the weld heat-affected zone during fusion welding. Nonetheless, there has been tremendous progress over the past two decades in improving the properties of steel welds. Currently, steel weld metal has exceptional strength and toughness for an as-solidified structure. It also has unusually good hydrogen cracking resistance. It is only in recent years, as we have introduced structural steels with 800 to 900 MPa yield strength that we have found hydrogen cracking in the weld metal rather than the heat affected zone. It is likely that both the exceptional toughness of steel weld metal and its resistance to hydrogen cracking are at least in part related to the distribution of ultrafine inclusions that are produced during rapid cooling of the weld.

We have also developed accelerated cooled steels which have extremely low carbon equivalent, and hence very low hardness in the heat-affected zone, with subsequent elimination of preheat and hence significant reductions in fabrication costs. Although our progress may have been slow, it is still steady. Thus, Dr. Weck may have been too pessimistic.

With regard to distortion of welded structures, there is a growing understanding of the use of secondary heating techniques to control the distortion while the weld is being made. Over time, this will no doubt lead to significant improvements and cost reductions in fabrication of welded structures.

It has long been known that diffusion bonds produce near perfect welds from the viewpoint of material properties. Nonetheless, these are very imperfect from the point of view of processing cost. In recent years there has been much more attention to diffusion brazing or transient liquid phase diffusion bonding. This is permitting the joining of many new aerospace materials. With regard to process control, we have made great strides over the past two decades in making use of both greater mechanization and greater automation of the welding process. This has resulted in reduced costs and greater quality and reliability. Methods of non-destructive evaluation have also improved significantly over the past two decades.

Conclusion

As seen in Table 1, over the past fifty years, the invention of new welding process technology has slowed considerably, as has the rate of improvement in weld properties. Nonetheless, the weldability of many materials has improved dramatically due to improved processing of the base material such as accelerated cooling of steels or greater purity or compositional control of the base material. Our ability to control the process has improved dramatically with subsequent reductions in cost. The result is that the quality and reliability of welded joints is significantly better today than at any time in history.

- 25% were invented prior to 1900
- 50% were invented 1900 to 1950
- 25% were invented 1950 to the present

Table 1
100 Welding, joining and cutting
processes listed in the *AWS Handbook*

Today, virtually anything can be joined if we are willing to pay the price. Nonetheless, a perfect weld is one which has identical properties as the base material and can be produced at zero cost. While we will never achieve such an ideal situation, we certainly must strive for the perfect weld. Our future progress over the next fifty years will be made by working on all aspects of the problem, including process development, metallurgy, properties, process control and design. The solution to welding problems of the future will involve a holistic approach which involves each of these fields of study. At the same time, the scientific community should return to visionary risk-taking approaches rather than merely elucidating the details of existing processes. With greater risk, there is greater reward. If we are to accelerate our progress in welding science and technology, we must be willing to assume greater risk in our research.

References

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